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Research Article

Experimental study on improving the utilization rate of underpasses of bundled linear infrastructure on Tibetan Plateau

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Abstract

Wildlife crossing structures (WCSs) are an important measure to protect biodiversity and reduce human-wildlife conflict, especially for bundled linear infrastructure. The aim of this study was to evaluate two "management and behavioral" factors (salt blocks and feces) in relation to two "structural factors" (underpasses' dimension and distance of bundled linear infrastructure) along Qinghai-Tibet bundled linear infrastructure (Qinghai-Tibet railway alignment runs parallel to the Qinghai-Tibet highway) and Gonghe-Yushu bundled linear infrastructure (Gonghe-Yushu expressway is parallel to the Gonghe-Yushu highway) using infrared cameras. Eight underpasses were monitored in the Qinghai-Tibet railway and six in the Gonghe-Yushu expressway, with half of the induced experimental group and half of the control group in each area. The monitoring shows that the Qinghai-Tibet railway area has richer species diversity than the Gonghe-Yushu expressway area. Salt block and feces induction experiments showed that the relative abundance index (RAI) of the experimental and control groups did not reveal significant differences in both areas. In addition, we found that the wider the width of the underpasses, the higher the utilization rate of kiang (*Equus kiang*) and wolly hare (*Lepus oiostolus*). And the distance from the adjacent linear infrastructure was positively correlated with the frequency of wolly hare, while no correlation was found with other species. In summary, this study found that salt block and feces induction could not improve the utilization rate of ungulates to underpasses of bundled linear infrastructure on Tibetan Plateau, and preliminary understood the factors affecting the utilization rate of underpasses.

Key words: Induction experiment, Qinghai-Tibet Plateau, railway ecology, road ecology, underpass, utilization rate, wildlife crossing structures

Introduction

Roads have become an important part of human society, with at least a quarter of the continental surface in Europe located within 500 meters of the nearest transport infrastructure (Torres et al. 2016; Medinas et al. 2019). However, while roads are beneficial to humans, studies have found that their impact on ecosystems is generally harmful (Krauss et al. 2010; Crooks et al. 2017; Barnick et al. 2022). For example, in Europe, an estimated 194 million birds

and 29 million mammals die on the roads each year (Grilo et al. 2020). At the very least, Asia's roads threaten the survival and reproduction of Asian elephant (*Elephas maximus*), tiger (*Panthera tigris*), leopard(*Panthera pardus*) and Asiatic cheetah (*Acinonyx jubatus venaticus*) populations (UNEP/CMS 2019; Carter et al. 2020; Grilo et al. 2021; Dodd et al. 2024). Roads have a fragmenting effect on wildlife habitat and could reduce tiger populations worldwide by up to 20% (Carter et al. 2020); roads act as a barrier to communication among cougar populations, resulting in a decrease in genetic diversity (Riley et al. 2014); Wildlife crossing structures (WCSs) built to facilitate wildlife crossing roads also fail to achieve the desired effect of animal communication (Gloyne and Clevenger 2001; Rosell et al. 2023). A large number of studies have proved that roads will affect wildlife in terms of individual casualties, habitat loss, population isolation, etc. (Wang et al. 2013; Clements et al. 2014; Laurance et al. 2014; Fernandes et al. 2022; Sur et al. 2022). Understanding the impact of roads on wildlife is therefore important for biodiversity conservation (Forman and Alexander 1998; Li et al. 2019; Zhou et al. 2023).

The Tibetan Plateau region is known as the third pole of the Earth and an important biodiversity hotspot. The region is rich in wildlife resources, including rare species such as Tibetan antelope (*Pantholops hodgsonii*), wild yak (*Bos mutus*), kiang (*Equus kiang*) and snow leopard (*Panthera uncia*) (Li et al. 2018; Zhang et al. 2021). However, in recent years, with the increasing intensity of human activities and the continuous expansion of transportation infrastructure construction, wild animals are shrinking their range and are sometimes injured by breaking into human facilities (Kong et al. 2013; Dai et al. 2022; Lu and Huntsinger 2023).

In order to reduce the barrier effect of traffic facilities, WCSs have been widely used as a mitigation measure, aiming to provide a safe passage for wildlife to traverse transportation infrastructure and help maintain biodiversity and habitat connectivity (Sawaya et al. 2013; Seo et al. 2021; Helldin 2022). There are 33 specialized WCSs along the Qinghai-Tibet railway, with many multifunctional WCSs that wildlife may also utilize, which were put into operation on 1st July 2006 (Wu and Wang 2006). Studies of existing WCSs in the Tibetan Plateau showed that ungulates on the Tibetan Plateau initially avoided the crossing structures and had a low utilization rate (Bu et al. 2013); with the passage of time, they gradually adapted to and utilized the WCSs (Xia et al. 2005; Li et al. 2008; Wu et al. 2009; Zhang et al. 2009); different species have different adaptation cycles and learning curves to WCSs, and Tibetan antelope takes the longest adaptation time (Wang et al. 2021); Some passages are not used by wildlife because they are too close to human activity areas (Yin et al. 2006; Feng et al. 2013).

The cost of constructing a WCS is high and it is challenging to alter its location, size, or structure after installation. Therefore, it is important to establish methods for maximizing the effectiveness of WCS (Bond and Jones 2008; Downs and Horner 2012; Wang et al. 2019). Previous research conducted worldwide has focused on determining the factors that influence the efficiency of WCS, such as size (Forman 1998), traffic volume (Van der Ree et al. 2011), noise and light pollution (Denneboom et al. 2021), habitat corridor (Ceia-Hasse et al. 2017), and landscape characteristics (Ascensao et al. 2018). It is important to find ways to increase the utilization of WCSs and further reduce the impact of roads on wildlife in case of bundled infrastructure. However, there are few studies about it.

Previous research on underpasses along the Qinghai-Tibet railway and the Gonghe-Yushu expressway revealed a high utilization rate of small mammals, such as wolly hares and Tibetan foxes, while the utilization rate of ungulates was found to be relatively low (Wang et al. 2018). As a result, efforts are being made to develop strategies to enhance the utilization rate of ungulates. Most ungulates are social animals and some also have the habit of licking salt blocks (Razali et al. 2020; Maro and Dudley 2022). Therefore, we are placing salt bricks to provide the necessary food for ungulates, and also attempting to create a similar scent of their own kind through feces in animal corridors, in order to determine if these measures can improve the utilization rate of animal corridors.

Infrared camera technology, as a non-invasive, effective and reliable tool, is widely used in WCSs assessment (Burton et al. 2015; Barroso et al. 2023). It can record the behavior and activities of wildlife in the WCSs, capturing precious data that are difficult to obtain directly under human observation (Laidlaw et al. 2021; Schmidt et al. 2021). In this study, we have used infrared camera technology to evaluate utilization of underpasses on the Tibetan Plateau region, and tried to test the effects of salt bricks and feces on improving underpasses utilization. Through the results of this study, we hope to have an understanding of the utilization of the underpasses by wildlife in the Tibetan Plateau, and provide a scientific basis for the design and management of the underpasses in this region. This will help reduce the impact of human activities on wildlife, maintain ecological balance and biodiversity, and promote the sustainable development of the Tibetan Plateau region.

Methods

Study area

Two transportation corridors in Sanjiangyuan National Park are selected. The first corridor is the Qinghai-Tibet highway(G109) and railway transportation corridor, which passes through the Yangtze River Source Park of Sanjiangyuan National Park. The second is the Gonghe-Yushu expressway and highway(G214) corridor, which passes through the Yellow River Source Park of Sanjiangyuan National Park (Fig. 1a).

The Qinghai-Tibet railway and highway(G109) are bundled linear infrastructure. Built in the 1950s, the Qinghai-Tibet highway(G109) carries 85 percent of materials entering Tibet and 90 percent of materials leaving Tibet (Xia et al. 2007). The Qinghai-Tibet railway, which started construction in June 2001 and operated in July 2006, has become another major transportation artery connecting Qinghai province with Tibet Autonomous Region after the Qinghai-Tibet highway (Ge et al. 2011; Wang et al. 2017a). The Qinghai-Tibet highway(G109), with no fence, accommodates an average of 2,002 vehicles daily in 2023 at speeds not exceeding 80km/h. The Qinghai-Tibet railway operates an average of 30–40 trains per day in 2023, reaching a maximum speed of 100 km/h. It is fenced and features numerous underpasses. In the study area, highway and railway run parallel without intersecting, and there are no human activities such as grazing (Ru et al. 2018; Wang et al. 2018) (Fig. 1c).

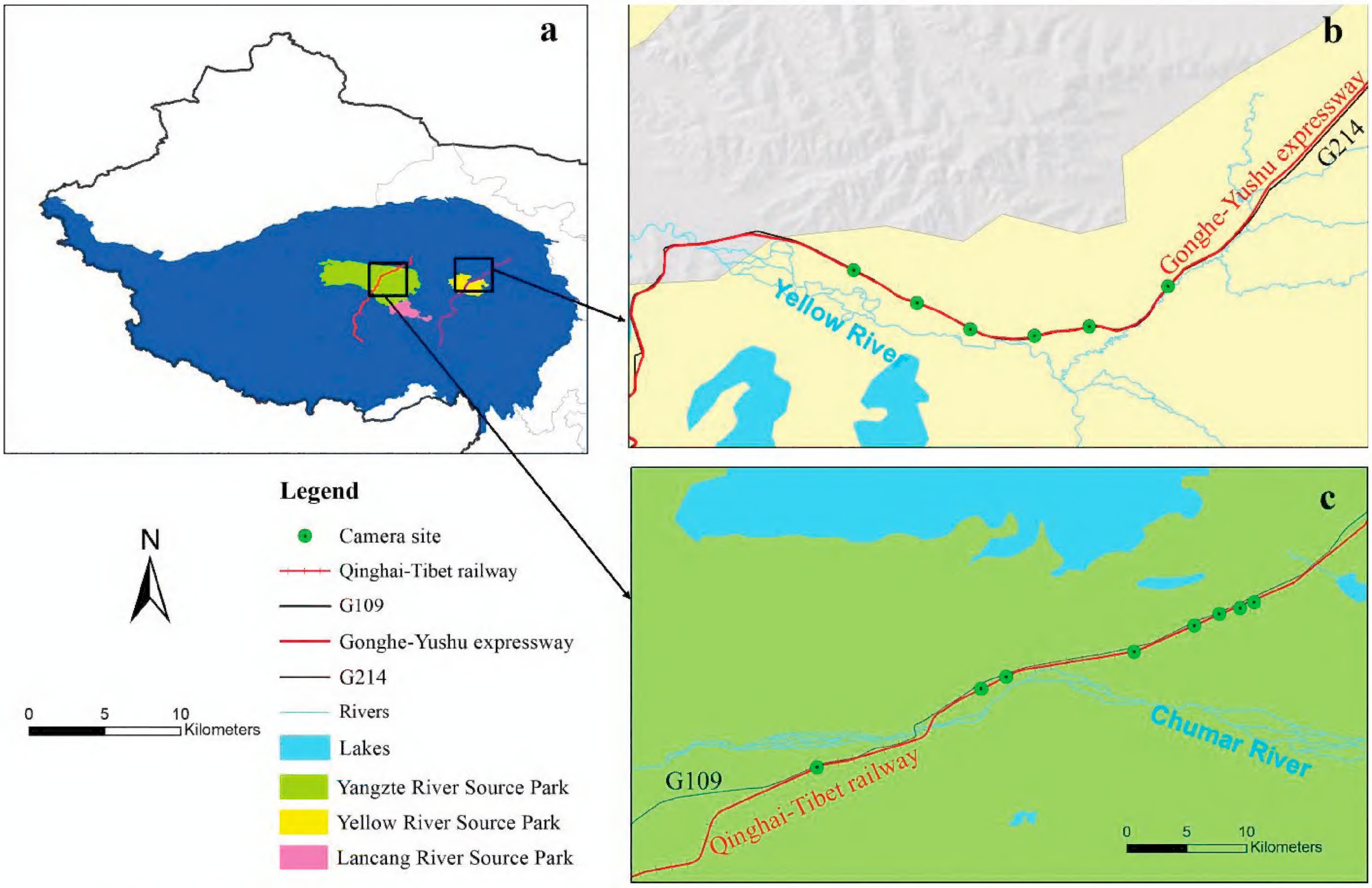

Figure 1. Schematic diagram of the study area and infrared camera sites **a** overall view of spatial relationship between two transportation corridors and Sanjiangyuan National Park (which includes Yangzte River Source Park, Yellow River Source Park and Lancang River Source Park) **b** Gonghe-Yushu expressway and highway research area and infrared camera sites **c** Qinghai-Tibet railway and highway research area and infrared camera sites.

The Gonghe-Yushu expressway and highway(G214) are also bundled linear infrastructure. The Gonghe-Yushu expressway operated in August 2017, becoming the first expressway in China to cross the permafrost region of the Tibetan Plateau. The Gongyu-Yushu expressway is entirely fenced and situated in grazing areas, leading to the construction of multiple underpasses to aid the movement of herders and animals. The maximum speed on this expressway is 100 km/h, with an average daily traffic of 1,800 vehicles. In contrast, Gonghe-Yushu highway(G214), which lacks fencing, sees an average of 1200 vehicles per day and has a specified speed limit of 80 km/h (Fig. 1b).

In the Qinghai-Tibet highway and railway transportation corridor, there are mainly 18 species of wild mammals living in the region. Including five species of national Class I protected, which are Tibetan antelope (*Pantholops hodgsonii*), wild yak (*Bos mutus*), kiang (*Equus kiang*), white-lipped deer (*Przewalskium albirostris*), snow leopard (*Panthera uncia*); Eight species of national Class II protected, which Tibetan gazelle (*Procapra picticaudata*), blue sheep (*Pseudois nayaur*), Tibetan argali (*Ovis hodgsoni*), Lynx (*Lynx lynx*), brown bear (*Ursus arctos*), grey wolf (*Canis lupus*) and Tibetan fox (*Vulpes ferrilata*) and red fox (*Vulpes vulpes*) (Yu et al. 2017; Xu et al. 2019). These animals have a wide range of distribution, and most of them have the characteristics of feeding, migration and breeding from low altitude to high altitude or from high altitude to low altitude with the change of season, and the migration needs to pass through the Qinghai-Tibet highway and railway transportation corridor. Among them, the long-distance seasonal migration characteristics

of Tibetan antelope are the most typical, and they move upward in May-June every year and back migration in July-August (Lian et al. 2011).

In the Gonghe-Yushu expressway and highway corridor, the main animals along the expressway are the Himalayan marmot (*Marmota himalayana*), pika (*Ochotona curzoniae*), Tibetan gazelle, grey wolf, Tibetan fox, and kiang (Yang et al. 2020).

In summary, numerous wild animals inhabit both corridors, highlighting the conflict between transportation and wildlife.

Monitoring methods

We selected 8 and 6 small underpasses with similar dimensions and similar surroundings on the two transportation lines of Qinghai-Tibet railway and Gonghe-Yushu expressway, respectively, and set up an infrared camera for each small underpass (Ltl6310 wide angle; Shenzhen, China), adjusted the parameters and position to ensure that the field of view can observe the entire cross section in a complete and clear way, and left after turning on the camera. Along Qinghai-Tibet railway, over a 50-kilometer stretch, we identified 8 underpasses of similar size, each at least 1 kilometer apart (Fig. 2a). The dimensions of each underpass, including length, width, and height, are detailed in Table 1. Along Gonghe-Yushu expressway, over a 30-kilometer stretch, six underpasses of similar dimensions were chosen, each spaced at least 1 kilometer apart (Fig. 2b). The dimensions of these underpasses are detailed in Table 2. Notably, there are no intersections between the expressway and the highway within the study area, and human activities are limited to grazing (Wang et al. 2020). We set a salt block under 4 underpasses on Qinghai-Tibet railway and 3 underpasses on Gonghe-Yushu expressway each, and scattered the surrounding animal feces (Kiang, Tibetan antelope, and Tibetan gazelle feces were collected using a shovel while still fresh) as the experimental group. The other underpasses were left without any manipulation and served as the control group. We wrote warnings next to the infrared camera to avoid destruction or displacement, and explained the situation to surrounding residents. The distance between two adjacent infrared cameras was more than 1km, and the study period was from July 2022 to April 2023. The camera parameters were set as follows: The shooting mode was camera + video, the shooting interval was 1 minute, and 3 photos and 1 video (10 seconds) were shot in succession.

Data analysis

We identified mammals in the infrared camera photos, because the photos of animals other than mammals were not clear, so only mammals were analyzed statistically. Taking 30 minutes as an event, species that appeared repeatedly within a single event were only recorded as one time, which is a valid photo. At each camera site, we calculated the relative abundance index (RAI) for each species;

$$\mathrm{RAI} = \frac{\sum_{i=1} N_i}{\sum_{i=1} \mathrm{Trapday}_i}$$

Trapdayi is the number of days taken at camera site i, and Ni is the number of valid photos taken at camera site i of a particular species.

Table 1. Basic parameters of underpasses on Qinghai-Tibet railway.

Camera number	Experiment or control	Length/m	Width/m	Height/m	Openness Index	Distance from other road/m
1	control	8	16	5	10	1000
2	experiment	8	12	3.5	5.25	206
3	control	8	16	3.5	7	183
4	experiment	8	8	3.5	3.5	342
5	control	8	8	3.5	3.5	210
6	experiment	8	8	3.5	3.5	173
7	control	8	8	4	4	218
8	experiment	8	8	5	5	230

Note: Openness Index = Width × Height / Length.

Table 2. Basic parameters of underpasses on Gonghe-Yushu expressway.

Camera number	Experiment or control	Length/m	Width/m	Height/m	Openness Index	Distance from other road/m
1	control	30	4	3.5	0.47	44
2	experiment	30	4	3.5	0.47	40
3	control	30	4	3.5	0.47	50
4	experiment	30	4	3	0.40	41
5	control	30	4	3.5	0.47	38
6	experiment	30	4	3	0.40	48

Note: Openness Index = Width × Height / Length.

Figure 2. Photos of the underpasses **a** Qinghai-Tibet railway **b** Gonghe-Yushu expressway.

First, we counted the number of species appearing at each camera site, compared the number of species differences between the Qinghai-Tibet railway region and the Gonghe-Yushu expressway region, and the number of species differences between the experimental group and the control group in each study region. Secondly, we used Kruskal-Wallis test to analyze the difference of relative abundance index (RAI) of each species in the experimental group and the control group to judge the effect of salt block and feces induction experiment. Finally, using the " lme4" program package in R, we used the generalized linear mixed model (GLMM) by setting the length, width, height, and distance from the adjacent road of underpasses as fixed effect factors, and the two barriers (railway and expressway) as random effect to analyze the relative abundance index (RAI) of each species and the basic parameters in certain underpasses, and judge the relationship between the parameters of underpasses and the utilization intensity of species. All data analyses were carried out in R 4.1.2, with $p<0.05$ as the significant criterion.

Results

Overall species recorded in the underpasses

Among the 8 monitoring sites of the Qinghai-Tibet railway, we successfully recovered the infrared cameras of 7 monitoring sites, and the infrared camera No. 4 in the experimental group was lost for unknown reasons. In total 1,403 shooting events of wild mammals belonging to nine species were captured by the seven infrared cameras. These included wild yak, which are listed VU by the IUCN, and Tibetan antelopes, Tibetan gazelles and mountain weasels (*Mustela altaica*) listed as NT. Among the species with a high RAI were Tibetan antelope (RAI:0.3362), woolly hare (*Lepus oiostolus*) (RAI:0.2105), wolf (RAI:0.1604) and kiang (RAI:0.1076); Species with a low RAI are mountain weasels (RAI:0.0020) and lynx (RAI:0.0020) (See Suppl. materal 1: table S1).

We successfully recovered all infrared cameras at 6 monitoring sites set up in the Gonghe-Yushu expressway. The six infrared cameras captured a total of 319 shooting events of five wild mammals. Kiang, Tibetan fox, wolf, lynx and woolly hare photographed are all species listed as LC by the IUCN. Among them, the species with a high RAI are the Kiang (RAI:0.1084); and the species with a lower RAI is the lynx (RAI:0.0040) (See Suppl. materal 1: table S2).

Results of induction experiments

In the salt block and feces induction experiment in the Qinghai-Tibet railway area, it was found that the mountain weasels were only photographed in the underpasses of the control group, but not recorded in the underpasses of the experimental group. In addition, by comparing the RAI of each species in the infrared cameras of the experimental group and the control group, it was found that the eight species photographed by both the experimental group and the control group showed no difference between the two groups (Fig. 3; Suppl. materal 1: table S3).

The salt block and feces induction experiment in the Gonghe-Yushu expressway area found that the woolly hare was only photographed in the underpasses of the control group, but not recorded in the underpasses of the experimental group. In addition, by comparing the RAI of each species in the infrared cameras of the experimental group and the control group, it was found that the four species captured by both the experimental group and the control group showed no difference between the two groups (Fig. 4; Suppl. materal 1: table S4).

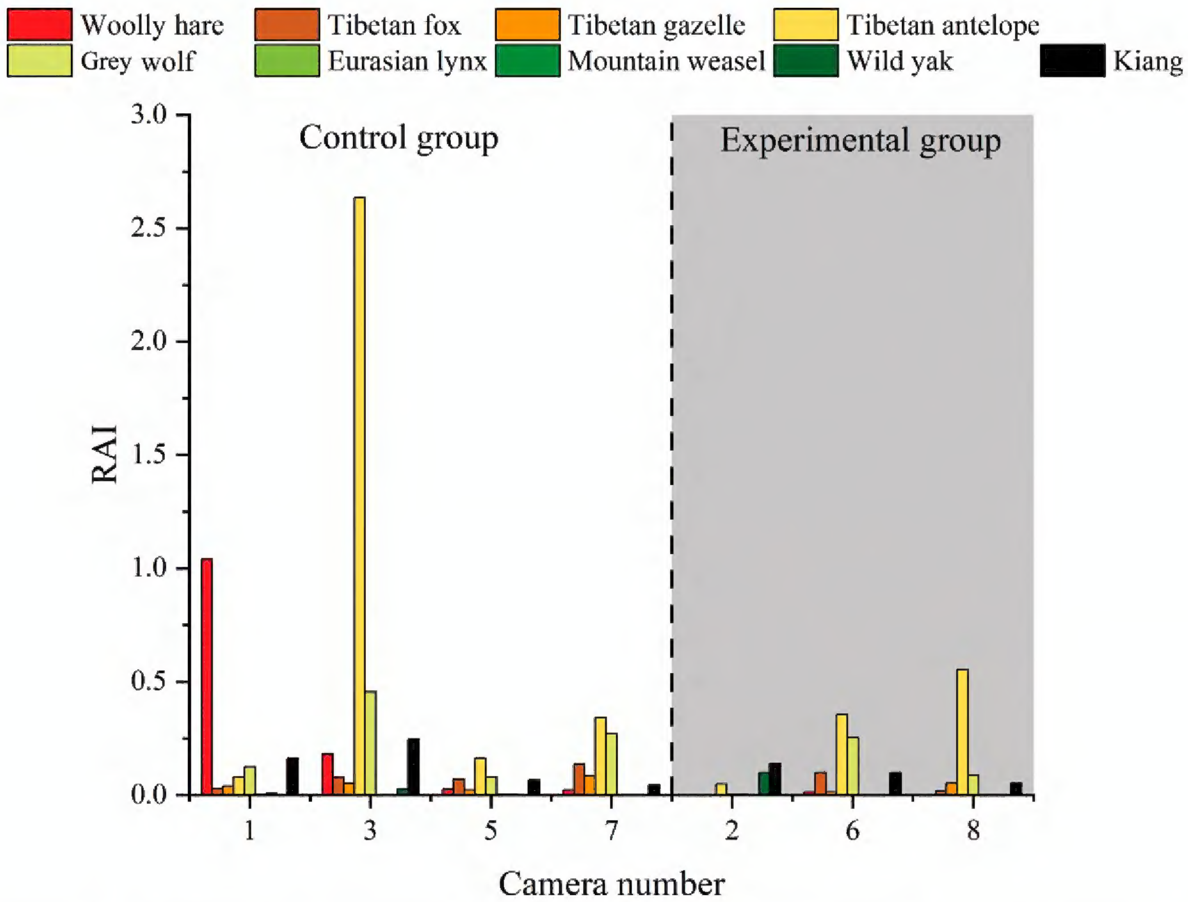

Figure 3. RAI of wild animals captured by infrared cameras on Qinghai-Tibet railway (Cameras 1, 3, 5 and 7 were the control group, 2, 6 and 8 were the experimental group, camera 4 was lost).

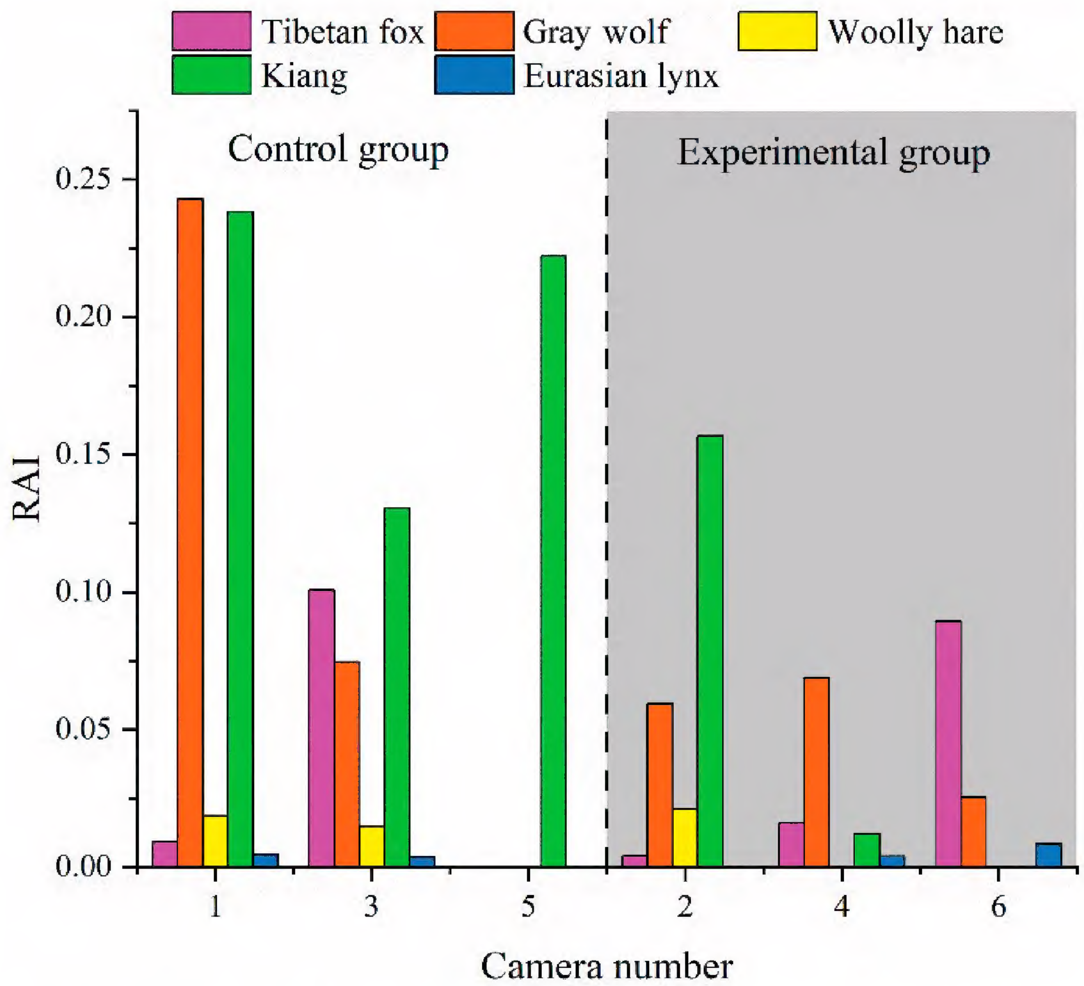

Figure 4. RAI of wild animals captured by Gonghe-Yushu expressway infrared camera (cameras 1, 3 and 5 were the control group, and 2, 4 and 6 were the experimental group).

Factors affecting underpasses' utilization by animals

By GLMM, we found that Tibetan antelope, Tibetan gazelle, Tibetan fox, Grey wolf, and Eurasian lynx did not show a correlation between the underpasses utilization and the basic parameters. The kiang showed that the longer ($z = 2.379$, $p = 0.017$) and wider ($z = 2.512$, $p = 0.011$) were the dimensions of the underpasses, the more frequently it appeared. Wolly hare showed a higher frequency of occurrence with longer ($z = 15.413$, $p < 0.001$) and wider underpasses ($z = 9.980$, $p < 0.001$), and greater distance from the adjacent road ($z = 14.848$, $p < 0.001$) (Table 3). Meanwhile, there was no difference in the relative abundance index (RAI) of the mountain weasel and wild yak in different underpasses, so no association with the basic parameters of the underpasses was analyzed (Table 3).

Table 3. GLMM between the relative abundance index (RAI) of each species and the basic parameters of underpasses in the infrared camera (p < 0.05 bold).

Species	Variables	Z	p
Tibetan antelope	Length	NA	NA
	Width	2.729	0.072
	Height	0.845	0.460
	Distance to other road	-2.168	0.119
Tibetan gazelle	Length	NA	NA
	Width	0.453	0.695
	Height	0.823	0.497
	Distance to other road	-0.687	0.563
Tibetan fox	Length	-1.200	0.230
	Width	-0.457	0.647
	Height	-1.192	0.233
	Distance to other road	0.210	0.833
Kiang	Length	2.379	**0.017**
	Width	2.512	**0.011**
	Height	0.596	0.551
	Distance to other road	-1.070	0.284
Woolly hare	Length	15.413	**<0.001**
	Width	9.980	**<0.001**
	Height	-1.247	0.212
	Distance to other road	14.848	**<0.001**
Grey wolf	Length	0.116	0.907
	Width	1.362	0.173
	Height	0.285	0.775
	Distance to other road	-1.092	0.274
Eurasian lynx	Length	0.298	0.765
	Width	0.004	0.996
	Height	-0.941	0.346
	Distance to other road	0.734	0.463

Discussion

Number of species differences in the study area of Qinghai-Tibet railway and Gonghe-Yushu expressway

Qinghai-Tibet railway falls under Yangtze River Source Park and the Gonghe-Yushu expressway falls under Yellow River Source Park of Sanjiangyuan National Park. Both of them belong to the alpine grassland ecosystem, the distribution of mammal species is very similar, and the species with higher and lower RAI values are similar, and both have relatively complete ecological chains. However, Tibetan antelopes, Tibetan gazelles, wild yaks and mountain weasels were found in the Qinghai-Tibet railway region, but not in the Gonghe-Yushu expressway region, indicating that the Yangtze River Source Park has a more complete ecosystem and better wildlife protection results than the Yellow River area. Among these four species, we have documented Tibetan gazelles and mountain weasels in the Gonghe-Yushu expressway area. The reason for not photographing them may be the high level of grazing activities along the expressway (Wang et al. 2020). However, there is almost no grazing activity in the current research area of the Qinghai-Tibet railway (Wang et al. 2018). Therefore, we urge for additional ecological protection to prevent the local extinction of these animals.

There is a significant amount of research indicating the impact of grazing on wildlife diversity (Waters et al. 2017; Pinto-Correia et al. 2018; Zhang et al. 2022). Similarly, studies in the Qinghai-Tibetan Plateau region have shown that increasing grazing intensity caused a decrease in biodiversity and ecosystem multifunctionality and that biodiversity and ecosystem function differed significantly between grazing intensities (Xiang et al. 2021; Liu et al. 2022; Liu et al. 2023). Therefore, it is crucial to focus on monitoring changes in grazing patterns in the study area. The construction of roads, which enhances transportation convenience and increases local grazing intensity, has been identified as a potential way in which roads can impact biodiversity.

Effect of salt brick and feces on inducing ungulates use in underpasses

We conducted salt brick and feces induction experiments on Qinghai-Tibet railway and Gonghe-Yushu expressway respectively, and the results showed that salt block induction experiments did not improve the utilization rate of underpasses in either of the two study areas. Our experimental results indicate that when the two underpasses are similar in size, salt brick and feces induction to attract ungulates that this does not improve the utilization rate of underpasses. The possible reason is that the soil on the Qinghai-Tibet plateau is salinized, and there are more ungulates licking the salt fields, and there is no shortage of salt (Zhang et al. 2012). The grasslands on both sides of the Qinghai-Tibet railway and the Gonghe-Yushu expressway have a lot of animal feces, so the feces at the entrance of the underpasses didn't make any difference. In addition, the Qinghai-Tibet railway and Gonghe-Yushu expressway have been operated for 16 years and 6 years, respectively. Wildlife is likely to have adapted to the underpasses. We surmise that salt blocks and feces may be effective for newly built underpasses and may speed up the adaptation of wildlife to underpasses, but this needs to be tested in future new build underpasses.

Due to improper WCS positioning or inappropriate WCS size, many animal WCSs that have been built have not achieved the expected utilization effect

(Clevenger and Waltho 2005; Denneboom et al. 2021). However, it is difficult to modify WCSs after they are built, so it is meaningful to take measures to improve the utilization rate of WCSs. However, there is currently no well-developed technology for creating WCS habitats, and our experiment exploring the impact of salt bricks and feces on ungulates is not significant. Further research is needed to further reduce the impact of roads on biodiversity.

Effects of underpasses size on utilization

Previous research results show that the utilization rate of WCSs mainly depends on the size of the WCSs itself and the degree of human interference (Yin et al. 2006; Feng et al. 2013). The research findings indicate that Siberian roe deer (*Capreolus pygargus*) and wild boar (*Sus scrofa*) (Wang et al. 2017b), roe deer (*Capreolus capreolus*) and moose (*Alces alces*) (Bhardwaj et al. 2020), elk (*Cervus elaphus*) and deer (*Odocoileus* sp.) (Ng et al. 2004; Mata et al. 2008) all prefer wider WCSs. Similar results were found in this study, where we found that the wider the width of the underpasses, the higher the utilization rate of kiang and wolly hare. Therefore, when constructing new underpasses in our study areas, it is advisable to make them as wide as possible, provided that conditions allow.

In addition, this study also found that the farther the underpasses were from the adjacent highway, the higher the utilization rate of wolly hare. This result is consistent with previous studies showing that ungulates on the Qinghai-Tibet railway prefer short, wide and high underpasses and farther away from the road (Wang et al. 2018). These results suggest that when building underpasses, if there is a parallel road next to it, the more distance there is between the underpasses and the road, the better.

In this study, to ensure the comparative effectiveness of salt block and fecal induction, underpasses with similar basic parameters were selected. Therefore, the differences in variables such as length, width, height, and distance from the road are not large enough, which may be the reason why the number of species showing correlation is small. Additionally, the underpasses' utilization rate is also related to its location. The underpasses' utilization rate on animal dispersal routes is high, while the underpasses' utilization rate in areas with high human interference is low. These factors can result in narrow underpasses having a high utilization rate, and wide underpasses having a low utilization rate. The behavior patterns of different species can also lead to different preferences for animal pathways. Therefore, we should approach the conclusions of this paper with caution and carefully understand the local species situation when practicing in different regions to obtain a more effective method.

Conclusion

This study was the first to test the effect of salt brick and feces on improving the utilization rate of WCSs on the highways and railways of bundled linear infrastructure on the Tibetan plateau. We found that there are a large number of wild animals living along the Qinghai-Tibet railway and the Gonghe-Yushu expressway, and that the underpasses can be used. The kiang and wolf are the main species using the underpasses. The species of wild animals along the Qinghai-Tibet railway are more abundant than those along the Gonghe-Yushu

expressway. We confirm that salt bricks and feces do not improve the utilization rate of underpasses significantly in Tibetan plateau. Finally, we observed that the incidence of wildlife use of the underpasses was related to the size and location of the passage itself, with wider underpasses and underpasses more isolated from other road disturbances being preferred by wildlife.

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Additional information

Conflict of interest

The authors have declared that no competing interests exist.

Ethical statement

No ethical statement was reported.

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Author contributions

Conceptualization, W.Y. and L.Z.; methodology, A.M. and W.Y.; software, A.M. and W.Y.; validation, A.M. and W.Y.; formal analysis, A.M. and W.Y.; investigation, A.M., W.Y and Y.Y.; resources, J.C., T.S., K.Y., and L.Z.; writing–original draft preparation, A.M.; writing–review and editing, J.C., Y.Y., T.S., K.Y., W.Y. and L.Z.; visualization, A.M.; supervision, W.Y.; project administration, L.Z.; funding acquisition, W.Y. and L.Z. All authors have read and agreed to the published version of the manuscript.

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Data availability

All of the data that support the findings of this study are available in the main text or Supplementary Information.

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Supplementary material 1

Supplementary information

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Data type: docx

Explanation note: **table S1.** Species of mammals that used small underpasses in Qinghai-Tibet railway area. **table S2.** Species of mammals that used small underpasses in Gonghe-Yushu expressway area. **table S3**. Kruskal-Wallis test results of RAI in the experimental group and control group in the Qinghai-Tibet railway region. **table S4.** Kruskal-Wallis test results of RAI in the experimental group and the control group in the Gonghe-Yushu expressway region.

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